Calibration of Color Dependent Bias and Status of Engineering Risk Reduction for SIM

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• Color Dependent Errors

Simplified illustration

Nominal balanced interferometer
Beam splitter transmission is balanced by Compensator plate
But not balanced at the picometer (~50 nanoarcsec) level

• Engineering Risk Reduction, building brassboard components and subsystems that are form, fit, function for space. (survive launch and space environment while maintaining performance)
Calibrating Color Dependent Biases

• SIM utilizes “chopping”. The science interferometer chops between ref star(s) and target star to remove a large range of systematic errors.

• But a systematic error that is due to a “color” dependent bias will not chop out if the ref star is of a different spectral type than the target star.

• To detect an Earth Clone @ 10pc, we need the end of mission error for SIM to be \(~50\) nanoarcsec. (Giving a SNR=6 for a 0.3 uas signal)
  – \(50\) nas is \(~2.4\times10^{-13}\) radian or \(1.5\) pm (picometer) for a 6m baseline

• \(50\) nas is needed after 100’s of hours of observation, over the 5 year mission. The change in star color we want to accommodate at 50 nas is K5 to F5. (4500K to \(~7500\)K)
Types of Color Dependent Biases

- Material dispersion (identified from the very beginning of SIM), the simplest to calibrate
- Geometric errors: CDCS (color dependent centroid shift of the angle trackers that keep the two arms aligned)
- Wavefront error in the fringe detector.
Material Dispersion

- The two arms of the Interferometer are not exactly identical.

Simplified illustration

Nominally balanced interferometer
Beam splitter transmission is balanced by Compensator plate

Imbalance remains at:
1) 1 extra mirror in left arm
2) Left arm has 2 AR coatings vs 1 in right arm before combination
3) Transmission through BS vs Reflection through BS

We made a decision to design the optics (and coating) to build SIM with Material dispersion < ~20nm p-p between 450nm and 900nm. And do everything else through calibration. (~2nm OPD shift from 4500K ~7500K)
What if We Did Nothing?

• We wish to measure the motion of the target star with very high accuracy?

• The OPD change is ~1nm when the color of the star changes from ~4500 (K giant ref star) to 5700K (G target star).
  – 1nm/6m ~ 30 uas. But for relative astrometry this fixed bias is not a problem if we adopt the same observing pattern at all epochs.
  – The G star would appear 30uas to the left of where it actually was, but it’d be the same 30uas at every epoch.

• If we wanted 2~3 uas accuracy, maybe nothing needs to be done.

• The error for exoplanets (and parallax/prop motion) occurs only if the color of the star changes over epochs. Since we eventually want 30~50 nas precision, we have to calibrate material dispersion.
SIM Fringe Detector

• After the light is combined, the fringe detector is a low resolution polarizing prism spectrometer.

450-900nm
80 pixels

Fringe modulation with PZT, measured with laser metrology with picometer precision.

Stars @ 1Kpc are slightly ~1% polarized by interstellar dust
Calibration of Material Dispersion

- With an internal white light source, record the interferogram for a ~100um change in OPD (in ~50nm steps) for each of the 80 spectral channels in the low resolution spectrometer.

Long stroke interferogram gives us the complex spectral response of each spectra pixel. Effective wavelength, Spectral width, Phase dispersion.
Dispersion Corrected Delay

• For each spectral channel
  – Delay(i) = Disp(i) + \lambda(i) * \phi(i)/2\pi

Calibrated by long stroke measurement
Disp & \lambda, calib in units of metrology laser \lambda

• \langle\text{Delay}\rangle = \sum (\text{delay}(i) * \text{weight}(i))/\sum(\text{weight}(i))
  – Weight(i) determined by photon-det noise

  – Angle \sim \langle\text{delay}\rangle/Baseline
Color Dependent Geometric Errors

- These errors are due to the effect we call CDCS, color dependent centroid shift, in the tip/tilt sensors that keep the two arms of the interferometer aligned.
  - Describe why the angle tracker shift with color
  - How that shift in alignment changes OPD.

Angle tracker CCD
(currently 1 arcsec pixels)
$$\frac{\lambda}{D} \sim 0.25 \text{ arcsec images}$$

Because images < pixel
Tip/tilt is measured using the normal quad-cell formula

$$X = \frac{(A+C-B-D)}{(A+B+C+D)}$$

But X in arcsec or radians depends on the width of the image $$\frac{\lambda}{D}$$. 
OPD Change with tip/tilt Change

- When the tilt of the stellar beam changes, it produce apparent OPD changes in 3 ways.
  - 1) Tilt* offset error
  - 2) \( \theta^2 \) error
  - 3) Change spectrometer \( \lambda \) calib

Ideally the metrology beam is at the center of the starlight beam, so that tilt error in the stellar beam does not cause an OPD error.

Currently we expect to keep the metrology and starlight centered to \( \sim 10 \mu \text{m} \), implying the color dependent tilt has to be \( < \sim 1 \times 10^{-7} \) radians, or \( \sim 1/150 \) of \( \lambda/D \).

The 2\(^{nd}\) geometric error comes from an angular deviation of the Stellar beam vs the metrology beam, error = \( \theta^2 \times L \).

Note a geometric error that is NOT color dependent will “chop out”, we only have to worry about the color dependent part of this error, due to a change in tilt from CDCS.
SCDU Top Improvements - I

- Color Dependent Centroid Shifts (CDCS) cause a color bias
  - We quantified, calibrated, and removed CDCS
  - The results was a smaller sensitivity to shear error and better spectral consistency

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Working model of the alignment-dependent error:

\[ \varepsilon = (S_i + L \cdot \theta_i) d\theta_i + (S_R + L \cdot \theta_R) d\theta_R \]

where:

- \( d\theta_{L,R} \:: \text{CDCS}_{L,R} \)
- \( S_{L,R} \:: \text{shear}_{L,R} \)
- \( \theta_{L,R} \:: (\text{met} - W_L)_{L,R} \)
- \( L \:: \text{effective pathlength} \)

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Uncorrected: PZT voltages change by 0.1 V; pointing change between filters is about 0.2 urad

Corrected: PZT voltages change by < 0.005 V; CDCS has been corrected to better than ~0.01 urad

Example: Right arm, y direction

CDCS is the apparent centroid shift when the color of the second target star is different (leading to different PSF size)

It is an artifact of coarse sampling of the PSF
Correcting CDCS

- CDCS biases are large because the PSF is undersampled by the CCD camera.
  - We’re increasing the pixel density critically sample the PSF. (2 pix per \( \lambda/D \))

- The fringe detector is an 80 channel spectrometer, so SIM measures the spectrum (and we can calculate the change in the shape of the PSF for different color stars, with one more piece of information)

- The PSF at the angle tracker CCD is non-ideal primarily due to wavefront errors in the optics (\(\sim\lambda/10\)). We need CDCS < 0.005 \( \lambda/D \) so knowledge of the wavefront to \( \lambda/200 \) is sufficient. (we expect the optics to stable \(< \lambda/200\), so this is a 1 time calibration during construction/alignment) Currently we’re planning to use focus diversity (in/out of focus images) to derive the wavefront errors.
SCDU Top Improvements - II

- **Shear** between metrology and white light causes sensitivity to pointing errors and couples with CDCS to cause bias.
- We also significantly improved **Metrology – White Light Angle Alignment**.

Before and After images show the improvements in pointing sensitivity data summary. The images illustrate the before and after adjustments, highlighting the reduction in sensitivity due to improved alignment.
Wavefront Error

- With a perfect wavefront, the central lobe of the airy pattern has zero phase and the 1st ring pi phase, etc. With an imperfect wavefront (eg I/20) the wings of the diff pattern will have phase errors comparable to lambda/20 ~30nm.
  - At a given pixel in the spectrometer, most ~60% of the light is from the wavelength band for that pixel, but 20% of the light is from wavelengths that should have landed in an adjacent pixel. If the spectrum changes, the amount of light from the adjacent pixel changes. We’re sensitive to a 1pm effect out of 30nm.

- The effective dispersion we see is a sum of material dispersion and wavefront error * diffraction.

- The result is that the spectrometer has to be several times more stable than if we just had to calibrate material dispersion. (eg a particular pixel is 600nm +/- 0.01nm)
SCDU Top Improvements - III

- **Fringe Placement** turns out to be a very important parameter: if the fringe moves after a long stroke, it corrupts the calibration.
- We developed the capability to measure the placement precisely, then measure the sensitivity, and finally control fringe placement.
- At this time, our capability placement to \(~ 2 \text{ milli-pixels}\)

\[
\delta_{\text{tot}} = \left( i \frac{\partial}{\partial x_{\text{com}}} + j \frac{\partial}{\partial y_{\text{com}}} \right) \varepsilon_{\text{spect}} \cdot \Delta x_{\text{common}} + \left( i \frac{\partial}{\partial x_{\text{rel}}} + j \frac{\partial}{\partial y_{\text{rel}}} \right) \varepsilon_{\text{WFE}} \cdot \Delta x_{\text{rel}}
\]

\[
= \nabla \varepsilon_{\text{spect}} \cdot \Delta x_{\text{common}} + \nabla \varepsilon_{\text{WFE}} \cdot \Delta x_{\text{rel}}
\]

- **Common mode:**
  \(~ 9 \text{ pm} / \text{mpix}~

- **Differential:**
  \(~ 3 \text{ pm} / \text{mpix}~

FTC illuminated by white light

FTC illuminated by He-Ne

Common mode:
\(~ 9 \text{ pm} / \text{mpix}~

Differential:
\(~ 3 \text{ pm} / \text{mpix}~

SCDU NA Performance Summary

- When all the calibrations are applied, we have experimentally demonstrated that the color dependent effects can be modeled to ~ 1 picometer ~ 30 nanoarcsec, for long integration times.
- The calibrations we do on the ground, and on orbit, are closely tied to how we plan to analyze the data. (Ground and on orbit calibration and data analysis is viewed as different parts of 1 task.)
SIM Lite Brassboard Status - Today

- Brassboards – form, fit and function to flight
  - Completed:
    - Guide-2 Telescope.
    - Internal & External Metrology beam launchers.
    - Fine Steering Mirror.
    - Beam Compressor & Bench.
    - Modulation Optical Mechanism (not shown).
    - Pathlength Optical Mechanism (not shown).
    - Double Corner Cube.
    - 30 cm Siderostat mirror.
    - Precision Structure Strut.
  - In process now:
    - Astrometric Beam Combiner (next 2 pages).
    - Metrology source pump diode assembly (not shown).
  - Planned but not yet started:
    - Optical Delay Line
    - Siderostat gimbal mechanism.
**SIM Lite Astrometric Beam Combiner (ABC) Acronyms**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMM1</td>
<td>Alignment Mirror Mechanism on arm 1</td>
</tr>
<tr>
<td>AMM2</td>
<td>Alignment Mirror Mechanism on arm 2</td>
</tr>
<tr>
<td>AT</td>
<td>Angle Tracker = ATA + ATC</td>
</tr>
<tr>
<td>ATA</td>
<td>Angle Tracker Assembly</td>
</tr>
<tr>
<td>ATC</td>
<td>Angle Tracker Camera head</td>
</tr>
<tr>
<td>CC1</td>
<td>Self-check corner cube 1</td>
</tr>
<tr>
<td>CC2</td>
<td>Self-check corner cube 2</td>
</tr>
<tr>
<td>CCA</td>
<td>Compensated combiner assembly</td>
</tr>
<tr>
<td>FM-AT1</td>
<td>Fold mirror on AT input (arm 1)</td>
</tr>
<tr>
<td>FM-AT2</td>
<td>Fold mirror on AT input (arm 2)</td>
</tr>
<tr>
<td>FM-IMET</td>
<td>Fold mirror on IMET path</td>
</tr>
<tr>
<td>FM-IP1</td>
<td>Fold mirror on input port 1 (arm 1)</td>
</tr>
<tr>
<td>FM-IP2</td>
<td>Fold mirror on input port 2 (arm 2)</td>
</tr>
<tr>
<td>FT</td>
<td>Fringe Tracker = FTA + FTC</td>
</tr>
<tr>
<td>FTA</td>
<td>Fringe Tracker Assembly</td>
</tr>
<tr>
<td>FTC</td>
<td>Fringe Tracker Camera head</td>
</tr>
<tr>
<td>IAM</td>
<td>IMET Alignment Mechanism</td>
</tr>
<tr>
<td>IMET</td>
<td>Internal Metrology beam launcher</td>
</tr>
<tr>
<td>SAM</td>
<td>Stimulus Alignment Mechanism</td>
</tr>
<tr>
<td>SCA</td>
<td>Stimulus collimator assembly</td>
</tr>
<tr>
<td>SIB</td>
<td>Stimulus Injection Beamsplitter</td>
</tr>
<tr>
<td>SM1</td>
<td>Shutter mechanism 1</td>
</tr>
<tr>
<td>SM2</td>
<td>Shutter mechanism 2</td>
</tr>
</tbody>
</table>

ABC Bench (purple) supports the ABC assemblies.
Astrometric Beam Combiner – Status

Fold Mirrors:
- SCA
- CCA

Shutter Mechanisms:
- (*)

Alignment Corner-Cubes:
- IMET
- FTA
- FTC
- ATC
- ATA

Scrubbing Mechanisms:
- AMM

(*) Motorized actuators:
- Was: 4/20/10
- Is: 7/15/10
- Cause: Aeroflex delay due to MSL
Brassboard Interferometer I&T

- Single Interferometer Test
  - Astrometric, Dynamics & Control (D&C)

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7734-168
MOM/POM/FSM (Delivered)

MOM = Modulation Optical Mechanism

POM = Pathlength Optical Mechanism

FSM = Fine Steering Mirror
PZT AC Life Test Completed

• PZT AC life test **stopped at 100B cycles (~5x one life)** as planned.

  —20 PZTs in life test.
  • 10 Active; 10 Inactive

  —~2 to ~3% degradation in deflection at end of life; very acceptable.

  —No failures.

  —Re-polling of the PZTs at 100V restores full deflection.
Summary

• The spectral calibration of SIM at 0.03 uas level was the last “laboratory” test. (driven by the search for 1 Mearth planets in the HZ around 60~100 nearby stars.) We still have a photon (SNR) limit of 1uas in a 1000 sec observation.

• The project has made considerable progress building flight qualified components and subsystem ~80% of the interferometric/metrology subsystems. (units have survived vibration and thermal/vac and maintained picometer performance.)